Report for 2002IL7G: Development and Validation of a 3D Coupled Hydrologic-Biogeochemical Model for Evaluation of the Impact of Water-Table Management on Nitrate Loads from Tile-Drained Agricultural Fields

- Conference Proceedings:
    - Feng Yue, A.J. Valocchi, R.J. Hudson, 2004, Physically-based 3D hydrologic conjunctive modeling of water flow in tile-drained agricultural fields in Groundwater Quality 2004 Proceedings, 4th International Conference, University of Waterloo, Ontario, Canada.
    - Hudson, Robert J.M., Albert J. Valocchi, David Hill, Feng Yue, Stephen P. Wente, Jaswinder P. Singh, 2002, "Modeling Denitrification in Agroecosystems of Central Illinois: Investigations at the Field and Watershed Scale" in EOS Transactions of American Geophysical Union, 84(47), Fall Meeting Supplement, p. F270-271.
- Dissertations:
    - Yue, Feng, August 2003, "Physically-based three dimensional hydrological conjunctive modeling of water movement in tile-drained fields," MS Thesis, Department of Civil and Environmental Engineering, College of Engineering, University of Illinois, Urbana, IL.
    - Yue, Feng, 2004, "Phsyically-based three-dimensional hydrological conjunctive modeling of water flow in tile-drained fields," M.S. Thesis, Department of Civil and Environmental Engineering, College of Engineering, University of Illinois, Urbana, IL.

Report Follows

Problem and Research Objectives

One of the most promising approaches to minimizing nitrate export to rivers draining agricultural watersheds is the use of water table management, or controlled drainage. The Illinois District of the USGS has conducted a field pilot study of the benefits of controlled drainage at an active farm in east-central Illinois. Two adjacent 40-acre plots, one with tile management and the other without, have been instrumented for collecting a variety of data. Modeling is required to fully interpret the field data and to extend the results to other farm conditions.

A portion of the project involves modeling studies with Drainmod-N, a widely-applied quasi 2-dimensional model. However, because raising the water table of a farm field may increase the amount of runoff and change its subsurface interactions with the larger-scale groundwater flow field, we hypothesize that a fully 3-dimensional model is required to properly quantify the hydrologic and nitrogen budgets of the study site. Our model will simulate both surface runoff/runon and subsurface flow between the adjacent managed/conventional plots (and adjacent fields), processes which can only be represented very approximately in DRAINMOD. The improved hydrology of the model will also allow us to improve our analysis of the N budgets of the two plots, since it accounts more accurately for nitrate exchange between adjacent plots by the above hydrologic paths and will better simulate differences in denitrification in surface ponds/puddles and in the subsurface due to increases in water and solute residence times.

Methodology

We plan to apply two different modeling approaches to analyze data being collected by USGS researchers from a paired set of agricultural fields with and without controlled subsurface drainage.

The first approach employs automatic calibration of an existing pseudo 2-dimensional groundwater/nutrient transport model (DRAINMOD and/or CERES-MAIZE) to investigate causes for the differences in nutrient export between the two fields. The second approach involves continuing development and application of a 3-dimensional model of hydrologic and solute transport.

Our emphasis is to develop a physically-based, 3-dimensional model that couples surface and subsurface flow with a biogeochemical model for nitrogen fate. The model will be calibrated and validated using the field data collected by the USGS. Our secondary objective is to apply our newly developed automatic calibration tools to DRAINMOD in order to understand the hydrology and nitrogen budgets of the controlled-drainage field study. We will attempt to quantify differences in denitrification using the model and calibrate field-specific parameters for use in the 3-dimensional model.

Principal Findings and Significance

3-DPhysically-Based Hydrology Model:

CHM3D was updated with an accurate and efficient numerical framework for modeling conjunctive flows at the Ford County drainage site. This framework is now based on the fractional stepping or operator splitting technique, which separates the governing equation of each flow equation into several computational steps. As a result, CHM3D consecutively solves 2D lateral surface flow, 2D lateral subsurface flow, 1D vertical subsurface flow, 1D tile flow, 2D lateral subsurface flow, 2D lateral surface flow in each numerical timestep. Each 2D flow takes half the timestep, while each 1D flow takes one whole timestep. The coupling among different flow processes were made through the 1D vertical subsurface flow that 1) takes rainfall and surface water either as an extended computational node when the surface becomes ponded or as an infiltrating flux at the boundary when the surface is dry; 2) and incorporates the flow to tiles as either an implicit or explicit sink with respect to the direction of this flow. Within this framework, different timesteps and numerical schemes can be applied for different fractional steps or operators depending on the scales and characteristics of each flow process. Therefore, CHM3D is not only tightly coupled but allows convenient numerical setup. Furthermore, numerically robust Alternating-Direction-Implicit method has been implemented for lateral flows, which occupies less computer CPU time to achieve good results.

N-Cycle Modeling:

To quantify nitrogen budgets for agricultural fields, we need to accurately estimate crop N uptake and net N mineralization in the soils in addition to hydrologic flows. In fact, crop N uptake and mineralization are both greater than N leaching in typical agricultural fields. After considering the available models, the CERES crop model coupled with the CENTURY soil organic matter (SOM) model was chosen for coupling to the hydrologic model.

A major part of our work is to develop a means of more accurately calibrating the SOM model using results from the Illinois soil N test (ISNT), which has been demonstrated to be a good indicator for N mineralization in agricultural soils. We are now in the process of modeling field studies of ISNT dynamics and agronomic rate studies to calibrate SOM model more accurately for conditions in Illinois and at the field site.

Field-Site N Budgets: In order to construct a nitrogen budget of the USGS field site, we are gathering additional data that will be analyzed using the models. Our analysis of water budgets for the fields suggests that there is considerable sub-surface flow from the controlled to the free-draining site. This suggests that nitrate leaching from the controlled field may actually be greater than expected from the tile measurements alone. In addition, soil sampling was conducted before planting in 2005 and samples analyzed for ISNT, which is a measure of readily mineralizable N. We are waiting to hear from the farmer about grain yields and fertilizer rates so we can complete the nitrogen budget for the site.